An Integrated Germanium-Based Optical Waveguide Coupled THz Photoconductive Antenna in Silicon

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Abstract: An integrated germanium-based optical waveguide coupled THz photoconductive antenna in a low-cost SOI process is presented with potentials to perform THz beam-steering. The radiated THz pulses achieve a FWHM of 1.14ps and bandwidth of 1.5THz.
OCIS codes: (130.0130) Integrated optics; (300.6495) Spectroscopy, terahertz; (250.0250) Optoelectronics; (040.5150) Photoconductivity; (110.6795) Terahertz imaging.

1. Introduction

In the past several decades, photoconductive antennas have been used for emitting and detecting THz waves. In order to push the bandwidth of THz pulses, ultrafast photo-conducting materials have been used due to their ultrashort carrier lifetime [1]. Radiation-damaged silicon-on-sapphire (RDSOS) and low-temperature-grown GaAs (LT-GaAs) are two common materials for building ultrafast photoconductive antennas [2]. However, the high cost of these materials prevents their use in high-volume applications. Moreover, RDSOS and LT-GaAs are not compatible with the low-cost 1.55µm lasers used in fiber-optic communications. These limitations prevent the use of THz pulse sources in applications that require low cost and high yield.

This paper presents a world-first, low-cost, silicon-on-insulator (SOI) photoconductive THz antenna excited by an optical laser pulse, coupled through an integrated waveguide instead of free-space coupling. The chip produces THz pulses with 1.14ps full width at half maximum (FWHM) and 0.337µW average power. A high-resistivity silicon lens is attached on the backside of the chip to collect the THz pulse, and a custom THz-TDS setup is used to characterize the THz pulses. In this design, an optical waveguide is used to guide femtosecond laser pulses to the core of a photoconductive switch, which is designed on an ion-implanted Germanium (Ge) thin film. This novel integrated waveguide-coupled photoconductive switch makes it possible to integrate the THz radiator with an on-chip laser. It also allows electronic beam-steering of THz pulses by delaying the optical excitation signal through an electrically driven optical delay line. Furthermore, by integrating optical delay components and photoconductive antennas on a single chip, the entire THz-TDS system can be replaced by a single pocket-sized module.

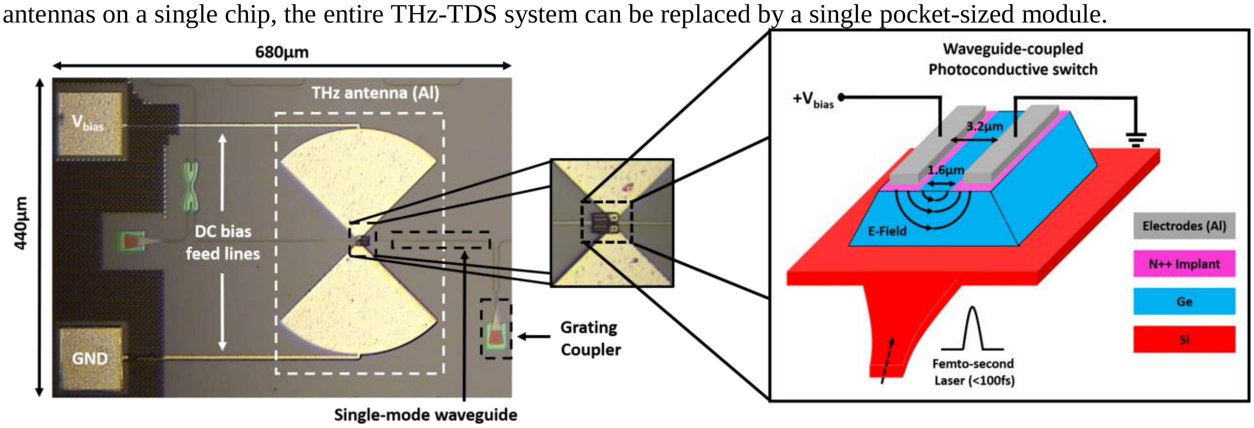

Fig. 1. Micrograph of the chip (left) and a 3D view of the waveguide-coupled photoconductive switch (right).

2. Design Architecture

As illustrated in Fig. 1, the photoconductive antenna consists of a grating coupler, a single-mode waveguide, a waveguide-coupled photoconductive switch, and a THz antenna with biasing bondpads. The total area of the chip is 680µm×440µm. In this design, a thin Ge film provided by the SOI process technology is used to absorb the light in the 1.55um wavelength regime [2]. Because Ge has a long photo-carrier lifetime, N++ implant ($4\times10^{15}cm^{-2}$) is added to reduce the photo-carrier lifetime to sub-picosecond [3]. Since the resistance of the N++ implant is small, the implant layer is split into two parts to prevent generation of a large DC current. In addition, the spacing between the electrodes is designed to be the minimum value allowed by the foundry, resulting in increasing the bandwidth of the photoconductive switch.

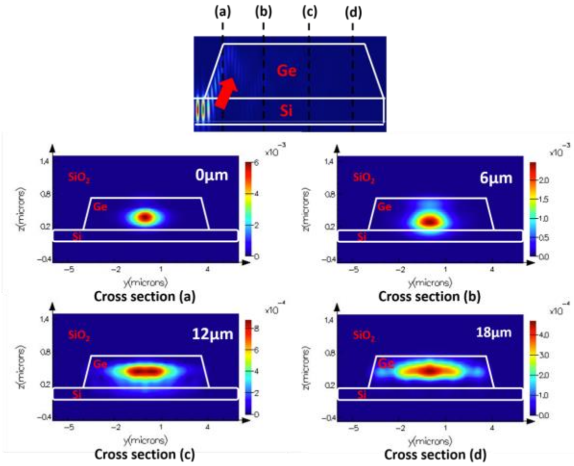

Fig. 2. Simulation results of light absorption in the Ge thin film (1.55μm).

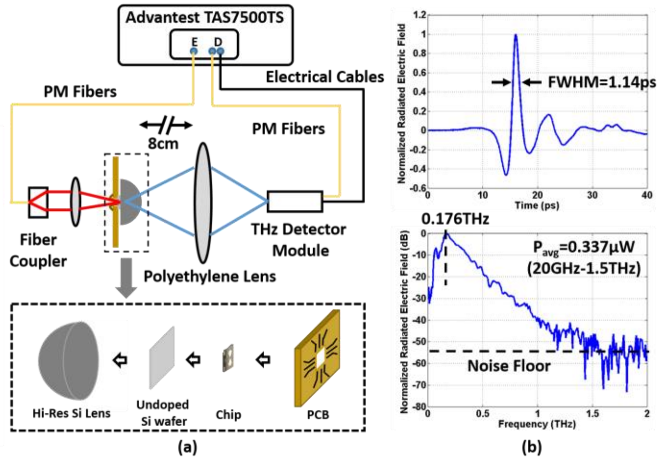

Fig. 3. Test setup and measurement results (bias voltage=3.5V).

In this design, the excitation laser pulse propagates in the waveguide before being absorbed by the Ge thin film. In order to achieve high conversion efficiency, the geometry of the Ge thin film in the photoconductive switch is optimized to maximize the absorption efficiency at the 1.55μm wavelength. Based on the simulation results, a 20μm long Ge film is used to fully absorb the light. Furthermore, the size of the light mode is expanded transversely along propagation, which reduces the transit time of the photocarriers by bringing them closer to the electrodes.

A bowtie antenna coupled to a silicon lens is designed for broadband radiation of THz pulses [4]. The antenna is fabricated on the top metal layer to minimize the conductive loss of the antenna and increase its radiation efficiency.

3. Results

The reported chip was fabricated by IME A*STAR through OpSIS foundry services. The chip was tested using an Advantest THz-TDS setup (Fig. 3(a)). A calibrated pyroelectric detector (Microtech Instruments) was used to measure the average power of the THz radiation (20GHz-1.5THz). A femtosecond laser pulse was coupled to the chip through the integrated grating coupler. With a maximum bias voltage of 3.5V, 1.14ps FWHM radiated THz pulses were measured with 1.5THz bandwidth and 0.337μW average power, as shown in Fig. 3(b). The measured conversion efficiency was 3.6×10^{-5}. Fig. 4 shows that increasing the bias voltage of the antenna enhances the bandwidth and power of the THz pulses. In this experiment, the maximum bias voltage was 3.5V, which was limited by the current capacity of the electrical vias used in the photoconductive antenna.

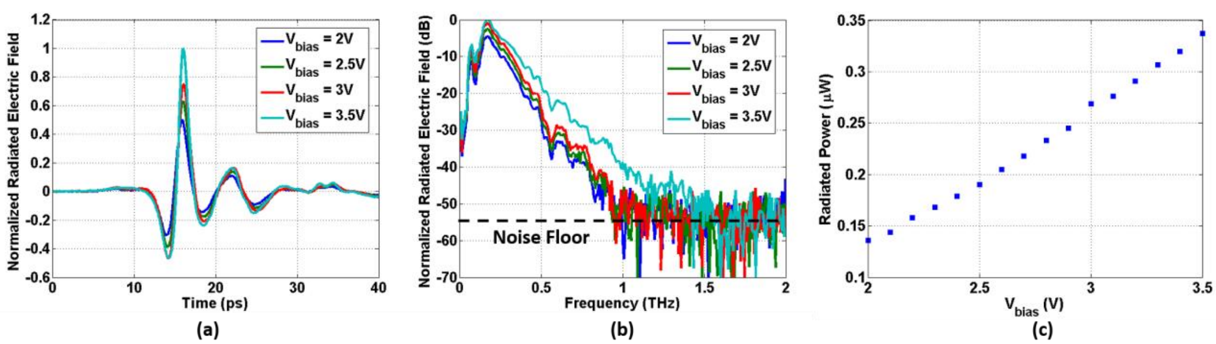

Fig. 4 (a) Time-domain pulse waveform, (b) frequency spectrum, (c) average radiated power with different bias voltages.

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